H008 Depth migration of SBL data

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Abstract

In order to migrate electromagnetic data from a low frequency controlled source, 3D electromagnetic Green's functions should be used since the near field effects may be large. Imaging principles of the correlation type do not have sufficient depth sensitivity to be used in a one-pass migration step. Depth sensitivity is increased if a non-local operator is introduced in the imaging condition. This operator accounts for the lateral propagation of the EM field in the high resistivity reservoir.

Introduction

The Sea Bed Logging (SBL) method is described by Eidesmo et al. (2002). The main idea is to use an active source to probe the underground for thin high resistive layers. Hydrocarbon filled reservoirs will typically have a resistivity that is one to two orders of magnitude higher than a water filled reservoir. It will also have a resistivity that is one to two orders of magnitude higher than the surrounding shale or mudrock, and this is sufficient to support a partially guided wave in the reservoir that will leak energy up to receivers placed on the sea bed.

The actual experiment is performed by dropping electric and magnetic sensors on the sea bed along a predetermined sail line and thereafter towing a horizontal electric dipole source along the line. The sail line starts at approximately 10 km before the first receiver and ends at approximately 10 km after the last receiver. Thus, all receivers have at least active source data with source receiver offsets of ± 10 km. The experimental geometry is similar to that of sea bed seismic data acquisition. It is well known that wave equation prestack depth migration of sea bed seismic data may be successful, given a good migration velocity model. Depth migration of sea bed EM data in a similar fashion is possible if the elastic wave equation is replaced by the Maxwell equations. However, additional problems must be addressed in depth migration of EM data.

First, the intermediate and high offset electromagnetic response from a hydrocarbon reservoir is not dominantly a reflection. This can be seen from the linear moveout of this event. The electromagnetic field excited in the reservoir behaves as a partially guided wave, propagating laterally through the reservoir and leaking energy back towards the receivers. The moveout is as for a refracted wave. Thus, Claerbouts imaging principle, which amounts to a correlation of up and down going energy in each subsurface location, is not ideal for imaging of hydrocarbon reservoirs with EM data.

Second, absorption and dispersion effects are much larger in EM data than in elastic data. Therefore, only low frequencies are available for imaging. Also, stability becomes a problem if absorption compensation is applied in depth migration.

Third, the phase behavior of the electromagnetic field must be respected. In the far field the electromagnetic field behaves as a ``seismic wave'' where phase increase linearly with propagation distance if the velocity is locally constant, however, for a typical overburden formation (1 Ωm - 3 Ωm) and typical frequencies (0.25 Hz to 2 Hz) the near field may reach several kilometers into the formation. For the nearfield of a horizontal electric dipole in a conducting medium, the phase does not necessarily increase linearly with propagation distance even if the velocity is constant. The nearfield is of course causal but appear to be nearly instantaneous for example in the depth direction. It is only in the farfield that the propagation velocity or phase gradient approaches that of a locally plane electromagnetic wave. To get the correct phase behavior of the fields, the Maxwell equations must be solved in 3D. In seismic depth migration of line data, a 2D propagator can be used with success, since the phase of the 2D wave extrapolator is very close to the phase of the 3D wave extrapolator. For EM migration this is not the case since the phase of the 2D Greens function differs everywhere from the phase of the 3D Greens function.

Tompkins (2004) reported migration of EM data using 1D propagators and Claerbouts imaging principle. The migration scheme discussed in the following differ significantly from that approach. We recognize that Claerbouts imaging principle is not directly applicable and that the imaging principle should be modified to account for the partially guided wave in the reservoir. We do migration with full electromagnetic 3D Green's functions that are calculated with a finite difference algorithm which solve for generally inhomogeneous media and also anisotropy if desired.

Theory

In Mittet et al. (1994), the elastic outgoing energy flux density of the misfit field was used as an error functional. The gradient of this error functional with respect to density and the Hooke's tensor could be expressed as correlations of an outgoing field with a reconstructed misfit field. The reconstructed misfit field was given by a Kirchhoff integral. This makes migration and the first iteration in an inversion procedure identical. Zhdanov and Portatgnuine (1997) have shown that a similar system can be obtained for the electromagnetic field using the electromagnetic energy flux density of the misfit field as the error functional,

$$\varepsilon = \int dt \oint d\vec{x}_r n_i \varepsilon_{ijk} \Delta E_j(\vec{x}_r, t) \Delta H_k(\vec{x}_r, t) \tag{1}$$

where n_i is the outward pointing surface normal, ε_{ijk} is the Levi-Civita tensor. The misfit field component $\Delta E_j(\vec{x}_r, t)$ is the difference between the measured electric field and the electric field predicted by the migration model at the receiver location, $\vec{x}_r$. The quantity $\Delta H_k(\vec{x}_r, t)$ is the corresponding magnetic misfit field. The gradient for conductivity can be expressed,

$$g_\sigma(\vec{x}) = \int dt E_m(\vec{x}, t) \Delta E_m(\vec{x}, t) \tag{2}$$

where $E_m(\vec{x}, t)$ is the outgoing field from the source, calculated in the background migration model and there is a representation theorem for the difference field,

$$\Delta E_m(\vec{x}, t) = \int dt' \int d\vec{x}_r n_i \varepsilon_{ijk} \left[G^{EK}_{mk}(\vec{x}, 0 \mid \vec{x}_r, t - t') \Delta E_j(\vec{x}_r, t') - G^{EJ}_{mj}(\vec{x}, 0 \mid \vec{x}_r, t - t') \Delta H_k(\vec{x}_r, t') \right] \tag{3}$$

Here G^{EK}_{mk} is the adjoint electric Green's tensor due to a magnetic source and G^{EJ}_{mj} is the adjoint electric Green's tensor due to an electric source. The gradient for resistivity is trivially obtained from the conductivity gradient. The first model update can be approximated to be in the negative gradient direction. In the following, the negative of the resistivity gradient is defined as the migrated image. Thus, if the migration results in a positive amplitude value at some location in the image, then a positive resistivity contrast is identified at that location.

Equation (2) is nothing but Claerbouts imaging principle, that is a correlation of an outgoing field with a field reconstructed from recorded boundary conditions. The parameter update in each iteration depends not only on the gradient, but also on the Hessian, which in principle is a non local operator on the gradient. Accounting for the Hessian is a non-trivial task and is not attempted here. The response from a hydrocarbon filled reservoir has a moveout which is consistent with a partially guided or refracted event. The given gradient expression is formally correct but numerical tests have shown that it is not very sensitive to the reservoir depth. Thus, this imaging condition may perform poorly in a one-pass migration scheme. One way around this is to modify the imaging principle to include the effect of laterally propagating energy. Here, this is done by introducing a non local operator of the form

$$I_\rho(\vec{x}) = \int d\vec{x}' \quad \Phi(\vec{x} \mid \vec{x}') E_m(\vec{x}',t) \Delta E_m(\vec{x},t) \tag{4}$$

where $I_\rho(\vec{x})$ is the image with respect to resistivity contrasts. It turns out that a model where we assume that the field propagate from the source down to the reservoir with a down going Green's function, couples with a laterally propagating Greens function in the reservoir which again couples with an upgoing Green's function that take the response to the receiver, can explain the main features of the SBL data for intermediate and large source receiver separations. Thus, EM data with small source-receiver offsets are not used in this migration scheme. The laterally propagating Green's function can be estimated with a plane layer modeling algorithm where the Greens function is excited and recorded at reservoir depth. Migration is then performed by transforming equation (3) and equation (4) to the frequency domain. Both phase and amplitude for the source current and the recorded EM data are used in the migration. Only phases for the Greens' functions are used. The total phase of the outgoing field from source to image location include the laterally propagating energy.

Results

Figure 1 and Figure 2 show results from depth migration of synthetic data. For the example in Figure 1, the true reservoir depth is 1500 m and for the example in Figure 2 the true reservoir depth is 2500 m. The reservoir locations are marked with white rectangles. The water depth is 500 m, but the effect of the air wave is not included in the synthetic data. It is assumed that proper up down separation is

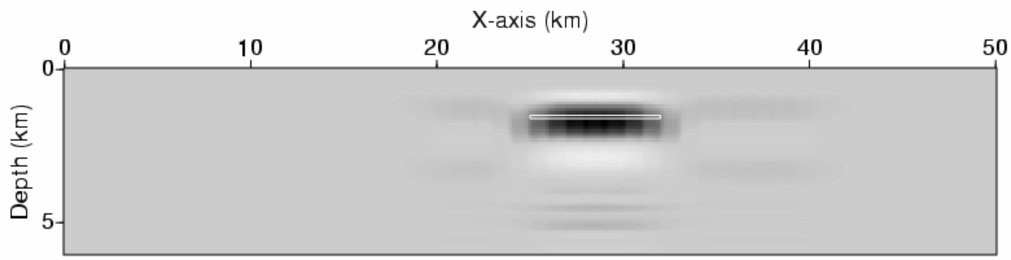

Figure 1

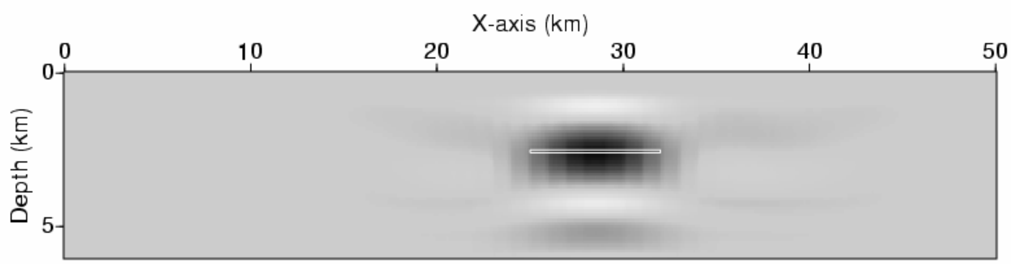

Figure 2

performed as a preprocessing step before the depth migration. For both cases the reservoir has a resistivity of 60 Ωm and the formation has a resistivity of 2.5 Ωm. In these images, black indicates increased resistivity compared to the background migration resistivity model. Data with equally spaced frequencies from 0.25 Hz to 2 Hz with a step of 0.25 Hz is used to create the images. Laterally, the reservoir seems to be well defined in both cases. Due to the limited number of frequencies we must expect side lobes to the reservoir image with depth or in some cases even replication of the reservoir image with depth. The effect does not seem to be too severe here. In both cases, the reservoir is slightly overmigrated, however, the method is clearly sensitive to true reservoir depth.

Figure 3 show migration of data acquired over the Troll field. The water depth is here 320 m and the air wave has a large effect on the data. In this case it is essential to separate in up and downgoing components of the EM field before depth migration. Up down separation requires that both electric and magnetic fields are recorded at each receiver station. After up down separation, the airwave appears in the downgoing component only. It is the upgoing component that is used as boundary condition in the migration. If up down separation is not performed, then the airwave will image falsely as high resistivity in the formation.

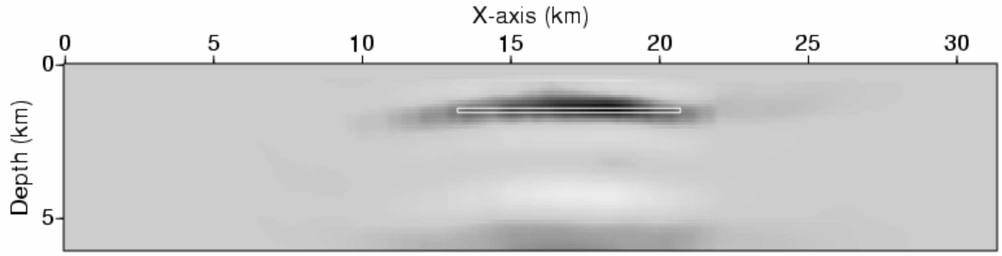

Figure 3

For this image, frequencies of 0.25 Hz, 0.75 Hz and 1.25 Hz were used. The lateral resolution is acceptable with the highest amplitudes at the known reservoir location. The vertical resolution seems even better than for synthetics. One reason for this may be that the background resistivity model is approximately 1 Ωm above and below the reservoir depth. Thus, locally higher spatial wavenumbers in the migrated EM field, as compared to the synthetic case, might increase resolution in depth. The background resistivity model was determined from forward modeling tests and plane layer inversion, matching data outside the known reservoir area. In this way it is ensured that the background migration model explains the main trends in the data when both source and receiver are far from the reservoir. Compared to the synthetics, the image of the Troll field is slightly undermigrated, indicating that we still need some optimization of the background resistivity (migration) model.

Conclusions

In order to migrate EM data from a low frequency controlled source, proper 3D electromagnetic Green's functions should used since the near field effects may be large. Imaging principles of the correlation type do not have sufficient depth sensitivity to be used in an one-pass migration step. Depth sensitivity is increased if a non local operator is introduced in the imaging condition. This operator account for the lateral propagation of the EM field in the high resistivity reservoir.

References

Eidesmo, T. , Ellingsrud, S, MacGregor, L.M., Constable, S., Sinha, M.C., Johansen, S., Kong, F.N., and Westerdahl, H., 2002, Sea Bed Logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas, First Break, 20,144-152

Mittet, R., Amundsen, L., Arntsen, B., 1994, Iterative inversion/migration with complete boundary conditions for the residual misfit field, Journal of Seismic Exploration 3, 141-156

Tompkins, M.J., 2004, Marine controlled-source electromagnetic imaging for hydrocarbon exploration: interpreting subsurface electrical properties, First Break, 22, Aug, 45-51

Zhdanov, M.S., Portniaguine, O., 1997, Time-domain electromagnetic migration in the solution of inverse problems, Geophys. J. Int. 131, 293-309